`LIGO-T040059-00-R`

DRAFT of Technical Proposal for the China Einstein Gravitational wave Observatory (CEGO)

Namelist

Abstract

This is a proposal for initiating a program of gravitational-wave astronomy in China by developing a new underground Gravity Wave detection facility.

The people signing this proposal have contributed to its contents and/or fully support the idea of a new Chinese Gravitational Wave Observatory, but their availability to contribute significant efforts to future work is not guaranteed.

1. Gravitational-wave astronomy: a nascent and promising field

1.1 Introduction

General Relativity describes the effect of gravity in terms of space-time curvature.[1] It has been verified by many observations, including the bending of starlight during eclipses, delay of propagation of radar in the solar system, and the perihelion precession of Mercury. General relativistic corrections are essential to maintaining the accuracy of the Global Positioning System (GPS). GR also portrays a dynamical picture of space-time structure, which predicts the existence of gravitational waves. The very existence of these waves is of great importance to our fundamental understanding of space-time.

Gravity is the weakest among all four fundamental interactions. The strongest gravitational waves are produced by the high-energy processes in the universe, for example coalescing binary black holes/neutron stars/white dwarfs, spinning neutron stars with non-vanishing ellipticity --- either isolated or within a binary, oscillations in nascent neutron stars, cosmological explosions such as supernovae, as well as density fluctuations from the early universe.[2, 3] Gravitational waves are generated by the bulk motion of masses or space-time curvature, and reflect a different aspect of the source as those revealed by electromagnetic radiations --- some gravitational-wave sources are not even visible from electromagnetic radiations. Some sources of gravitational waves are also expected to reside in the highly non-linear regime of general relativity, which is currently not well understood. The gravitational-wave stochastic background can also probe an era much earlier than the Cosmic Microwave Background (CMB), since the interaction of gravitational waves with matter is much weaker than electromagnetic waves (and therefore they decouple from the rest of the universe at a much earlier time).

The effect of gravitational waves on closely separated (distance shorter than the wavelength) free test masses can be characterized by a time-dependent tidal force, which can be described by h, the *strain* it induces on the proper distance between two masses. (Formally h is the amplitude of the space-time metric perturbation.) As they arrive at the Earth from their distant sources, gravitational waves become extremely weak. For example, a pair of merging neutron stars near the center of our galaxy will generate a characteristic amplitude $h\sim 3\times 10^{-17}$ at around 100 Hz,[2] yet such a “ loud” event is estimated to happen in our galaxy only once per 10^4--10^5 years,[4] which means we must include at least $\sim 10^4$--10^5 “ Milky-Way-equivalent” galaxies to be able to detect such an event in one year’s observation time.

In summary, gravitational waves, aside from their unique significance for fundamental physics, can also provide an entirely "new window" to the universe --- the energetic, exotic and the early. However, the detection of gravitational waves requires extraordinary measurement sensitivity.

1.2 Brief history and current status of gravitational wave detectors

The quest to detect gravitational waves began in the 1960s, when Weber build the first resonant mass detectors to sense the tiny oscillations gravitational waves induce at their resonant frequencies (at a few hundred Hz to several kHz). *[Please add brief review of research activities at Zhongshan University and IHEP.]*

Although these laboratory-scale (typically a few meters) resonant bars were severely limited by thermal fluctuations, as well as their narrowband implementation, they spurred the development of both gravitational wave experiment and theoretical studies of sources. In the mean time, indirect evidence of gravitational waves has been discovered in the famous Hulse-Taylor binary pulsar,[5] whose orbital period shrinks according to the prediction of general relativistic gravitational radiation-reaction.[6] Three more binary neutron star systems have been discovered since then that will merge in less than the current age of the universe, including a recent one in which both objects are pulsars.[7, 8]

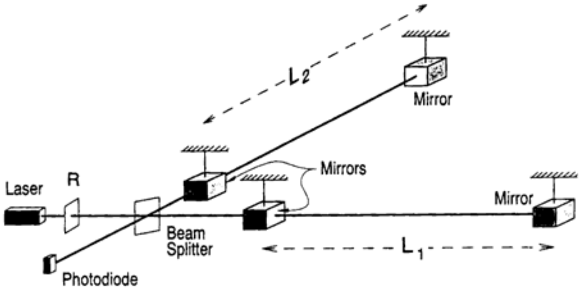

Fig. 1 Schematic plot of an interferometric gravitational-wave detector. Michelson interferometry is used to monitor tiny displacements induced on mirror-endowed test masses, which hang from seismic isolation structures.

Starting in the 1970s, practical development of a different type of detectors, laser interferometric gravitational-wave detectors with kilometer-scale arm lengths (interferometers for short), was started by Forward[9] and Weiss.[10] These detectors use laser interferometry to measure the strains induced by gravitational waves on mirror-endowed test masses hanging from seismic isolation stacks (Fig. 1). Despite the technological challenge and the cost of construction, these devices have the fundamental advantage provided by their long baseline that the displacement of the optics is proportional to the product of the gravitational-wave strain and the arm length. Optical interferometry also provides the possibilities of broadband and tunable-band operations, which dramatically increases their scientific potential with respect to resonant bar detectors. Kilometer-scale baselines have been further enhanced by inserting Fabry-Perot cavities into the interferometer arms,[11] and by adopting more advanced optical techniques such as power and signal recycling.[11, 12]

After three decades of development, an international network of long-baseline laser interferometric gravitational-wave detectors, consisting of LIGO in the USA,[13] VIRGO (an Italian-French collaboration),[14] GEO600 (a German-British collaboration)[15] and TAMA300 (Japanese),[16] are beginning operation. The LIGO interferometers have reached sensitivity of $h \sim 10^{-21}$ at 150 Hz, a factor of 2 away from its design goal at this frequency, and are expected to reach its design goal in one year. First coincident science runs between the LIGO and GEO600 interferometers have been completed,[17] yielding initial upper-limit results.[18] Coincident science runs between the LIGO and the TAMA interferometers have been performed as well. Virgo, now in commissioning phase, is also expected to begin GW observation runs within the year and make coincidence science runs soon after that. Astrophysical estimates suggest that it is plausible for first-generation interferometers to make a convincing detection over an operation of three years. In particular, each interferometer in initial LIGO is already able to detect a neutron-star-binary inspiral up to 14 Mpc away (this is averaged over relative orientations of the source and the detector; optimally oriented, it can reach 22 Mpc), with an expected rate of once per several years to once per several tens of years.[3, 4] It is generally believed that upgrades must be made before a rich program of observational gravitational-wave astronomy can be carried out.

An upgrade of LIGO (named Advanced LIGO) is planned for around 2008. [19] Advanced LIGO is being developed and operated by the LIGO Scientific Collaboration. Advanced LIGO is planned to improve the sensitivity by a factor of 15, by lowering various thermal noises and the seismic noise, and by increasing optical power; the signal-recycling optical technique, currently being used by GEO 600, is also part of the upgrade to be performed. A factor of 15 increase in sensitivity implies an increase of detection volume by 15^3~3000, which makes Advanced LIGO plausible to detect compact-binary inspirals in a regular basis, to detect continuous waves from several Low-Mass X-ray Binaries or from known and unknown pulsars, and to detect possible gravitational waves from cosmological supernova explosions.[20] Similarly Virgo is expected to undergo an equivalent, but more incremental, upgrade in a similar time scale. In addition, a second-generation detector, the Large-scale Cryogenic Gravitational-wave Telescope (LCGT), is planned in Japan and is waiting for funding.[21]

Ground-based interferometers are generally believed to be limited to high frequencies (somewhere above 1 Hz), by Earth- or human-generated Newtonian gravity-gradient noise (Newtonian Noise, or NN, for short).[22] To extend sensitivity to lower frequencies, a space-based interferometer, the Laser Interferometer Space Antenna (LISA), has been planned by ESA and NASA for the coming decade, with launch scheduled for 2012. [23] LISA targets gravitational waves with frequencies from 10 μHz to 100 mHz. LISA uses three drag-free satellites in heliocentric orbit with separation of $\sim 10^6$ km linked by laser beams in a flexible interferometric configuration. Other efforts to detect gravitational waves with even lower frequencies include pulsar timing[24] and the detection of CMB polarization.[25] NASA financed a design study for space instruments (BBO - 2025) to start covering, from below, the physics rich frequency gap between LISA and the interferometers based on Earth's surface.

1.3 Summary of proposed research program

The main emphasis of our proposed research program is to study the feasibility of Low-Frequency (LF) GW detection down to around 1Hz, by building an underground interferometer facility.

For gravitational-wave interferometers build above ground, the Newtonian (seismic gravity-gradient) Noise has been shown to fundamentally limit their sensitivities to 10—20Hz.[22] As we shall show in the next section, interesting astrophysical sources do exist below such frequencies. It was recently realized that an underground interferometer can plausibly suppress the seismic gravity gradient noise by a large factor **(**10^6**)** and make the interferometer sensitive to frequencies as low as 1 Hz.[26] It is therefore clear that underground, LF interferometers, covering this novel frequency range, would have a great impact in strengthening the present global GW detector network, extending its frequency coverage and filling from above the frequency gap between LIGO and LISA.

In addition to evaluating the extent to which the Newtonian Noise can be suppressed, other interferometer technologies relevant to LF detection must also be studied before such an interferometer can be designed and realized, including:

- Developing suspension systems that provide LF seismic isolation and low suspension thermal noise.[27, 28]
- Manufacturing mirrors with low coating thermal noise,[29] internal thermal noise[30] and thermoelastic noise.[31, 32]
- Designing optical configurations that provide low optical noises (radiation-pressure noise and shot noise) in low frequencies, which may require using mirrors with large masses (a few hundred kilograms or more).

At the same time, the likely astrophysical impact of a LF interferometer should also be investigated.

It has to be kept in mind though, that a fall back solution with an initial implementation of a "regular" GW interferometer (a Virgo-like or Advanced LIGO-like interferometer covering the 10--20 Hz to ~5 kHz GW frequency detection range) would, by itself, have plenty of scientific justification to build this facility. Although underground facilities are not required simply to build regular GW detectors, making a regular inteferometer in an underground facility is simpler than over ground because of the quieter and more shielded environment. An additional regular interferometer would by itself be precious to strengthen the present GW detection network. Whether LF interferometer or not, a Chinese gravitational-wave detector will be strongly welcome to the international GW detection community, which would extend its best assistance and support.

It also needs to be noted as well that building long tunnels requires large diameter tunnels, and these can host multiple interferometers, each dedicated to different frequency ranges. The construction of an underground facility is naturally not limited to the implementation of a single GW detection interferometer. A sequence of progressively more advanced interferometers can be implemented in the same tunnel either like in the LIGO Hanford facility (two interferometers in the same tube) or in independent, parallel, pipes. It is likely that a facility capable to host LF GW detectors, and open to the international community, would, at some stage, attract external contributors installing their own specialized detectors.

The emphasis of the rest of the document will be on LF interferometers to cover the 6 to 30 Hz frequency range. This aim is believed to be achievable with present technologies, without pushing too much the technical envelope. Although there are no known fundamental limits impeding a lower frequency interferometer, extending down to 1Hz (the presently estimated cutoff due to Newtonian Noise), the technical extrapolation is large and the problem is not addressed in this report. This document describes a possible progression toward the completion of a scientifically successful interferometric detector. This progression, of course, will be refined along the way, as the scientists involved will become more and more expert and aware of the true technical and scientific difficulties and as possible observations may generate different priorities.

The progression towards a finished detector is divided in three main stages, each of which would produce very valuable results and return to China and to the international scientific community, even if changing financial realities where to slow or even impede the following stages.

The first stage is to train scientists on GW detection at the existing facilities. Their arrival would substantially enlarge the pool of scientists interested in gravitational-wave detection. It has been declared that these scientists are welcome either as individuals, or as Chinese collaborating groups, in all the major existing facilities. The quality of Chinese scientists would virtually guarantee a suitable and rapid scientific return for China. Their contribution to the international GW detection network would be openly recognized and greatly appreciated.

The second stage would be to build a mid-size developmental interferometer of the scale of the LIGO 40 meter interferometer. This enterprise would train the Chinese scientists to build their own interferometer and prepare them for the installation of the large instruments in the final underground facility. The judicious choice of scientific aim for this developmental interferometer would produce novel techniques and its results may then be implemented in the new interferometer or even in any or all of the existing ones.

Finally, the realization of the facility and the actual implementation of a sequence of LF (or even simply a "regular") interferometer(s) in the facility would generate an impressive, obvious and undiscussed Chinese contribution to the international GW astronomy effort. A scientific enterprise of such a magnitude will undoubtedly attract many Chinese, and even foreign, students and young scientists.

As a last point it should be stressed that an effort in such a frontier enterprise like GW detection will certainly force technical advances in China in critical fields ranging from ultra stable Lasers, advanced controls, precision optics, sophisticated data analysis, and even fine mechanics on top of the probable fundamental scientific achievements.

2. Scientific case for an underground, low-frequency gravitational-wave interferometer

2.1 Astrophysical motivation

Until recently, it had been considered impossible to measure GW on Earth at frequencies below 10 to 20 Hz, due to Newtonian gravity-gradient noise. Advanced LIGO, optimized for detection of neutron-star binaries and sources at several hundred Hz, has its most sensitive band above 20—30Hz. On the other hand, the space-based interferometer, LISA, is being designed to be sensitive to the frequency range between 0.1 mHz and 0.1 Hz. In addition, with its present launching date of 2012, LISA will not produce GW signals any earlier than 2014.

NASA has recently approved a design study for an ambitious LISA follow-on mission (the Big Bang Observer – timeframe 2025) with peaked sensitivity at ~0.3 Hz, which bridges the gap between LISA and LIGO from below. The primary scientific goal of BBO is the detection of a primordial gravitational wave stochastic background generated in the very early universe, since in this frequency band the confusion noise from galactic and cosmological neutron-star binaries is the lowest.[33, 34] In this section, we discuss the astrophysical interest of LF detection, assuming that gravity-gradient noise can be suppressed by a large factor and become negligible down to 1Hz, and leave technical feasibility for the next section.

As we will see, low-frequency interferometers are sensitive to different sources from, or different regimes of the same sources as high-frequency interferometers, and may therefore provide many new exciting scientific possibilities. However, these possibilities have not been studied previously, and should be investigated carefully in the next couple of years. Such investigations should constitute an important evaluation of the scientific significance and prospect of Earth-based low-frequency gravitational-wave detection.

2.1.1 Compact-binary inspirals: range vs. mass, HF vs. LF interferometers

Among all plausible astrophysical sources for gravitational-wave interferometers, the inspiral of compact binaries is the best understood and one of the most promising.[20, 35, 36] The inspiral of compact binary objects are driven by gravitational radiation reaction: the binary orbital radius shrinks adiabatically, due to losses of energy and angular momentum, while the orbital frequency increases;[37] the orbit also tends to circularize under radiation reaction.[38] The gravitational waveform from compact inspirals is a " chirp", a quasi-periodic function with gradually increasing frequency and amplitude. The dynamics and waveforms of compact binaries at early stages of inspiral can be calculated by Post-Newtonian techniques,[39] their accuracy degrade as the two objects come closer to each other.[40] As the orbital radius further shrink, at one point circular orbits become unstable (the inner-most stable circular orbit, or ISCO), which is formally the end of the inspiral phase and the start of the merger (or plunge) phase. Non-perturbative approaches, like numerical relativity, must be used to give the correct description of the merger phase.[41] Following the merger, after perturbations on the final black hole are damped sufficiently by outgoing gravitational waves, its dynamics can again be described analytically as quasi-normal-mode oscillations.[42]

The ISCO of a compact binary cannot be defined rigorously due to ambiguities of Post-Newtonian expansions at the end of the inspiral,[40, 43] except in the case of a low-mass object inspiralling into a massive object –- for which the ISCO can be defined from the stability of the geodesic orbits around the massive object. For non-spinning black hole (Schwarzschild), the (quadrupole) gravitational-wave frequency corresponding to the ISCO is $4400/M$ Hz where M is the mass of this black hole (in unit of solar mass).[35] In the general case (even for comparable-mass binaries), or in case of spinning black holes, one may still use the above formula for a rough estimate for the ending frequency of the inspiral signal, by using as M the total mass of the binary.

More quantitatively, in the leading Post-Newtonian order, in frequency domain, the inspiral waveform is proportional to $|\tilde{h}(f)| \sim \Theta(4400\mathrm{Hz}/(M/M_\odot) - f)\mathcal{M}^{5/6} f^{-7/6}$, where `M` is the so-called chirp mass,

$\mathcal{M}=M\eta^{3/5}$, and η=□$_1$□$_2$/M^2, the mass ratio; the step function Θ □□presents the cut-off at ISCO frequency.[35] For the same mass ratio η, the larger the total mass, the larger the signal strength, but the lower the ending frequency. When matched-filtering is used the Signal-to-Noise Ratio that can be obtained by a detector with noise spectral density $S_h(f)$ is then

$$\mathrm{SNR}=\left[\int\frac{|\tilde{h}(f)|^2}{S_h(f)}df\right]^{1/2}\propto\mathcal{M}^{5/6}\left[\int^{\frac{4400}{M}}\frac{f^{-4/3}}{S_h(f)}d\ln f\right]^{1/2}$$

From this equation, we can see two points:

- For any detector, as we start from low masses, as long as 4400/M exceeds the detection band the SNR grows proportional roughly to $M^{5/6}$ (which is close to linear in M), due to the stronger signal strength of binaries with higher masses.
- The SNR peaks at a certain M, when 4400/M is well inside the interferometer's most sensitive band. As M grows further, loss of SNR due to the decrease of the inspiral ending frequency begins to overweigh the increase of signal strength at lower frequencies.

These considerations are relevant to SNRs of binaries at a fixed point in the universe. The larger the SNR here, the farther away in the universe we can see (proportional to SNR at this fixed point), and the larger volume we include (proportional to SNR^3, until we reach cosmological distances).

Now let us examine the equation in more detail. Suppose we have a broad-band low frequency interferometer with comparable $f\,S_h(f)$ to Advanced LIGO, then for binaries with very low masses (for which the ISCO cut-off is not relevant for both interferometers), we can get similar or even better SNR to Advanced LIGO. [Note that on the RHS we integrate over d ln$f$ instead of df.] For binaries with larger masses, however, our low-frequency interferometer will have much better SNR because the ISCO cut-off affects first the higher-frequency interferometers when M becomes larger. As a consequence, a low-frequency interferometer can see much farther by being able to detect binaries with much higher masses.

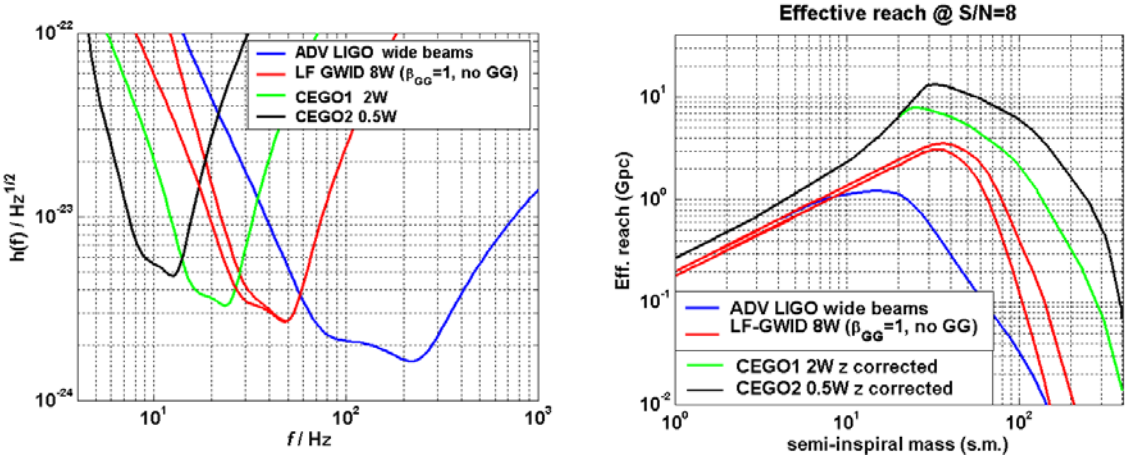

Fig 2. Four interferometers with Advanced-LIGO topology optimized for four different frequency bands with decreasing central frequency. Left panel: noise spectra; for comparison, the Newtonian Noise is included for only one of the configurations (red curve). This interferometer configuration presents two separate sensitivity curves, corresponding to times of higher and lower seismicity. Right panel: effective reach of the same four configurations for equal-mass binaries as a function of individual black-hole mass.

	ADV-LIGO wide beam	LF-GWID	CEGO1	CEGO2
Arm length (m)	4000	4000	4000	4000
Laser power (W)	125	8	2	0.5

Last susp. stage length (m)	0.6	1.5	6	12
Mirror material	Sapphire	Fused Silica	Fused Silica	Fused Silica
Mirror mass (kg)	40	73.5	120	200
Mirror Q	200-10^{6}	200-10^{6}	200-10^{6}	200-10^{6}
Mirror coating phi	2-10^{5}	2-10^{5}	2-10^{5}	2-10^{5}
Mirror radius (cm)	15.7	21.5	24.8	24.8
Mirror thickness (cm)	13	23	28.2	47
Input mirror transmit.	0.005	0.005	0.005	0.005
Beam radius[3] (cm)	9.4	12	14	14
Signal recycling mirror transmit.	0.07	0.07	0.07	0.07
Signal recycling cavity detuning phase	0.12	0.52	0.95	1.55

Table 1A: list of optimization parameters of the four interferometers shown in Fig 2.

	S/N for (1.4 +1.4)$M_{\odot}$ inspirals at 200 Mpc
Adv LIGO wide beams	10.7
GWID	10
GWID no GG	11.4
CEGO I	13.1
CEGO II	12.9

Table 1B. Integrated S/N for the four interferometers shown in Fig. 2. [cumulative performance, to be added, in preparation]

In the left panel of Fig. 2, we show the noise spectra of four possible interferometer configurations with same optical topology as Advanced LIGO, but with parameters optimized for low-frequency detection (see Table 1A.) We assume a 4-Km baseline, for best comparison with LIGO. (An underground GW detector may have longer arms, with correspondingly longer reach in the Universe.) For comparison reasons, a "minimal" variation maintaining the Advanced LIGO topology has been performed. The performances of the four interferometers are calculated using `BENCH`, the simulation tool for Advanced LIGO.[44] We show noise spectra only from the ideal optical noises, assuming all technical noises can be suppressed. Different topologies, optimized for LF GW detection, would certainly improve the detection capabilities and/or simplify the instrument.

In the right panel of Fig. 2, we show the detectable volume of each of these detectors, for equal-mass binaries, as function of individual black-hole mass. Just as expected, with frequency band 10 times lower than that of Advanced LIGO, we are able to see binaries 10 times more massive, obtaining a range roughly 10 times farther, reaching more than 10 Gpc (z~3). In Table 1B, we list the S/N's achievable by these interferometers for neutron-star binaries [(1.4 +1.4)$M_{\odot}$] at 200 Mpc, compared with Advanced LIGO. [Given the nature of the `BENCH` program, these numbers should not be taken as absolute but only used as indicative ones and for a relative evaluation of the performance between different interferometer configurations.]

2.1.2 Scientific output from a single LF interferometer

We shall now discuss in more detail possible astrophysical significances of both high-mass and low-mass compact binaries, and other scenarios.

From inspirals of high-mass binaries (individual mass exceeding 15 solar masses) The fact that we can see a much larger volume must be combined with an astrophysical estimate of the event rate of such binaries, since it is typically believed that such black holes (intermediate-mass black holes, or IMBHs) cannot form directly from collapses of typical stars. At least three mechanisms have been proposed for black holes with these masses to form: inside globular clusters assisted by three-body interactions,[45-47] from the collapse of massive stellar objects that form in dense clusters through runaway collisions,[48] and from the collapse of metal-free binary stars in the early universe.[49] All mechanisms are considered plausible to provide reasonable event rates for Advanced LIGO (which is not efficient for such binaries), and therefore should provide much higher event rates for LF interferometers. It should be noted that IMBH binaries in globular clusters may form with significant ellipticity,[46, 50] and may not completely circularize when they enter the CEGO band (for high *e* systems we have approximately $e \sim 1/f$).[50] While detecting eccentric binaries may require extra data-analysis efforts,[51] more general relativistic effects (like precession of the periaps) can be explored by studying their waveforms. To summarize, detecting IMBH binaries, with higher event rate or up to farther distances, will have the following possible scientific output:

- Higher-SNR events will allow us to examine the inspiral/merger/ringdown waveforms in more details, therefore providing a stronger comparison between theory and experiment.
- Possible binaries with elliptic orbits may allow us to explore the physics of such orbits.
- Detecting a sufficient number of binaries up to z~3,[52] or detecting them in several interferometers at different locations coincidently,[53] may allow us to perform cosmology tests up to that redshift.
- The overall statistics (rate, as well as distribution of parameters) of detected events of IMBH binaries will provide precious information for stellar and galactic evolution theories.

From inspirals of low-mass binaries (individual mass below 15 solar masses) Although we get similar SNR from our LF interferometer, the SNR is accumulated at much lower frequencies, therefore over a much longer period of time. In the leading order, the time left before the final coalescence, as a function of the current gravitational-wave frequency, is

$$\tau = \frac{5}{256\pi^{8/3} f}(\mathcal{M} f)^{-5/3}$$

where the chirp mass M has to be converted into units of second. As we see here, the lower the mass, the longer the binary stays in a particular frequency band. The 5/3 power provides a rather sharp dependence on mass.

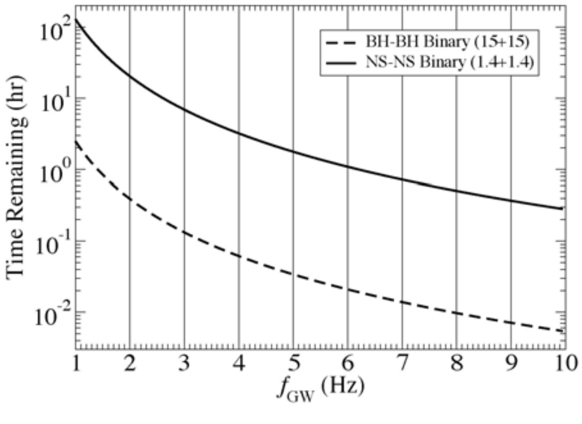

Fig 3. Remaining time before merger (leading order) of NS+NS and BH-BH inspiral as a function of instantaneous gravitational-wave frequency emission.

In Fig. 3, we plot the τ □. for $(15+15)M_\odot$ and $(1.4+1.4)M_\odot$ binaries. From the graph, we see that for black hole binaries more massive than $(15+15)M_\odot$, the inspiral spends less than 2.5 hours in the band above 1Hz, less than 8 minutes above 3Hz and less than 19 seconds above 10Hz; while for neutron-star binaries, the inspiral spends 5.4 days above 1Hz, 6.9 hours in the band above 3Hz, and 17 minutes above 10Hz.

The extension in time of inspiral signals for low-frequency interferometers provide both difficulty in data analysis, and potential scientific benefit, so must be studied in more depth. Since gravitational-wave detectors are built on the Earth, which spins and circles around the sun, the antenna pattern of the detector is time dependent, and the wave is Doppler-shifted in a time-dependent way. These have been known and crucial problems for pulsar data analysis in ground-based gravitational-wave detectors[54, 55] and for LISA data analysis.[56] The time dependence of the antenna pattern can be taken into account automatically for all sources in the sky by using the so-called $\mathcal{F}$-statistic prescription,[55] but the Doppler shift can only be taken care of by searching over sky patches: carrying out demodulations according to where the hypothetical source lies in the sky.

In the data analysis for pulsars, Doppler shift poses a great obstacle for an all-sky coherent search for unknown pulsars. In our case, however, since our interested frequency is much lower, and our observation time is much shorter, computational problems related to Doppler shifts may not be very important. As an order-of-magnitude estimate, let us consider NS binary between 1Hz and 10Hz, which continues for roughly T=5.4 days. For Doppler shift due to Earth's motion around the sun, it is plausible that we can approximate it by a linear acceleration process, therefore the associated Doppler shift can be absorbed into an effective "spin-down" parameter, i.e., an extra term in the phase of $h(f)$ proportional to a power of f. For the Doppler shift due to the Earth's rotation, since T is longer than one day, it must be taken care of more explicitly. Since the projection of the detector's speed along the source direction oscillates sinusoidally with a period of one day, the Doppler shift red shifts the frequency half the day, and blue shifts it the other half. The accumulative phase must be no more than $v_E f / c \times 0.5\text{day} \sim 0.7$ cycle (where we use $f \sim 10$Hz for a conservative estimate). This seems plausibly treatable with a moderate number of templates.[57]

An additional opportunity for LF detection arises when at least one of the objects is spinning, and with its spin misaligned with the orbital angular momentum. In this case, both the spin and the orbital angular momentum will precess.[58, 59] The orbital precession will modulate the waveform, often significantly. The precession phase, in the case of $\mathbf{L}>\mathbf{S}$, is approximately proportional to $1/f$ and there will be more cycles when at lower frequencies.[58, 60] Data analysis for spinning binaries had been considered very challenging, since the number of parameters involved in the template bank is large (the masses, initial spin orientations, spin magnitudes, initial orbital orientation, detector orientation, etc.). This is currently an active field of research, and recent development has shown that it is plausible in the near future to perform with high efficiency a coherent templated search for spinning binaries in initial-LIGO-like interferometers.[61, 62]

Suppose we do succeed in solving in real time the data analysis problems, we should be able to detect inspirals of low-mass BH-BH, NS-BH and NS-NS binaries at a much earlier stage, this may have the following scientific consequences.

- The time dependence of the antenna pattern may provide us another way of determining the sky position of the binary, in addition to the existing multi-detector triangulation methods.
- The determination of sky position, along with our capability of detecting early-stage inspirals, may provide " early warnings" to electromagnetic (EM) telescopes for the EM counterparts of NS-BH and NS-NS binary mergers. For example, for a NS binary, if we can gather enough SNR up to 6 Hz, then we will have ~1 hour to point the telescopes.
- We can test Post-Newtonian dynamics of compact binary objects at lower frequencies. For example, for spinning binaries, the large number of precessional cycles may allow us to study general relativistic spin-orbit coupling in more details, and measure the spins of the objects to more accuracy.

From low-mass objects (several solar mass) inspiraling into high-mass objects (~ 1000 solar mass)

In this scenario, due to the very low mass ratio, inspiral dynamics and waveforms can be evaluated using black-hole perturbation theory, instead of post-Newtonian expansions.[63] This allows us to explore a different regime from usual inspirals to be detected by surface interferometers.

From merger and ringdown of binaries with even higher masses

In addition to being able to reach z~3 by detecting inspirals of intermediate black holes, a LF interferometer may reach a much further distance by observing merger and ringdowns of black-hole binaries with even higher masses.[3, 35, 36]

For these sources, it may also be plausible for LISA to observe their inspiral phase (in the higher end of its detection band), and act as a trigger for CEGO to search for their merger/ringdown signals. Note that, in the search for burst-like signals, having an idea of the time-of-arrival and rough shape of the signal will increase detection power dramatically. For example, for a $(500+500)M_{\odot}$ binary, the last year of inspiral starts from 5.2 mHz (roughly middle of LISA band), while the inspiral terminates at 4.4 Hz, with merger and ringdown waveforms well within the CEGO facility band limits.

2.1.3 Multiple co-located, frequency-separated LF interferometers and coincident operation with HF interferometers

Interferometers with nearly exclusive frequency coverage

Roughly speaking, the operation of any two of the interferometers in Fig. 2, acting on different frequency bands, can be seen either like two separate interferometers running in coincidence or like a single interferometer integrating signal to noise over a wider frequency band. Let's look at the two points of view separately.

1. LIGO has built two widely separated (3000 Km) interferometers running in parallel simply because at low S/N level it is necessary to have a coincidence to validate the signal (Virgo will join soon as a third coincidence interferometer). Two co-located interferometers sensitive to separated frequency ranges will collect signals in separate time periods. The detection of temporarily contiguous signals in independent, frequency separated, interferometers would be equally compelling than observing coincidence in spatially separated, but temporally coincident, interferometers. Given the similar S/N of the four proposed interferometers, detection of even a weak, borderline, in any of the interferometers would force the detection in all the others (or be rejected).
2. Looking at two completely frequency separated interferometer as a single, wider bandwidth, interferometer means that for a given inspiral (say a NS-NS inspiral) for which both individual interferometers had, say, integrated S/N=8, the tandem operation would yield S/N=11. This increase of S/N capabilities translates, for a fixed S/N detection threshold, into much larger effective reach and covered Universe volume or faster detection rate. Of course adding more frequency independent interferometers running in parallel would yield progressively growing performance.

As another realization of point 2, for massive binaries whose inspiral signal cannot reach the detection band of HF interferometers, being able to detect their inspirals in a LF interferometer can serve as triggers for offline searches in HF interferometers of their merger and ringdown waves, thereby increasing the chance of detecting and studying them in HF interferometers. Even more dramatically, parameters of a binary extracted from the LF interferometer can be used to constrain the search and allow to dig deeper into the noise spectrum of a HF inteferometer, in real time or offline, to optimally detect the high-frequency component with smaller number of templates.

Interferometers with common frequency coverage

Two LF interferometers with common frequency coverage can provide the possibility of carrying out cross-correlation searches of primordial stochastic backgrounds.[64, 65] GWs decouple from the cosmic plasma at the Planck time, corresponding to a cosmic time $t \sim 10^{-43}$ sec and energy scale $T \sim 10^{19}$ GeV; detecting the stochastic background can probe fundamental physics at unprecedented energy scales (future particle physics experiments, such as LHC, will probe the behavior of fields at energy scale < 10 TeV). It is important to notice that the signal produced by scale invariant stochastic backgrounds scale as $f^{3/2}$, which highlights the importance of accessing low frequencies.

Standard inflation predicts a stochastic background several orders of magnitude below the sensitivity of current ground-based interferometers. In addition, the LISA frequency band the standard GW background will be buried by an astrophysical gravitational-wave background due to many unresolvable neutron-star and white-dwarf binaries.[33, 34] However, various alternative models give potentially detectable stochastic backgrounds;[64] confirming the prediction of any of these models will have huge scientific impact. Since these models are varied and can be highly tunable, it is crucial to have detectors covering all frequency bands.

A window of GW cosmic background detectability, free from neutron-star and white-dwarf confusion noise, is expected in the bandwidth between that of terrestrial surface GW detectors and that of LISA --- this has led to the idea of the NASA Big-Bang Observer (BBO) mission, the follow-on mission of LISA. Although the long-term goal of BBO is to enhance the sensitivity dramatically (reaching $h \sim 10^{-27}$ at ~0.1Hz) and ultimately allow the direct detection of standard-inflation stochastic background, certain short-term goals, like exploring/constraining possible stochastic background from alternative theories, detecting IMBH binaries, and detecting low-frequency components of NS-NS binaries, may aready be fulfilled by the CEGO facility without the need to go into space.

Note that interferometers suitable for background searches should have nearly the same orientations, much less than 45 degrees rotated from each other, and be located much closer to each other than a quarter of a GW wavelength in order not to lose coherence.[65] Of course a co-located twin interferometer would have complete coherence, but there would be questions about “technical” coherence of the noise signal. At 10 Hz the “coherence” distance is of the order of 7,000 Km, which, if properly oriented, would make it an ideal opportunity for coincidence runs with a LF version of LCGT in Japan, the other planned underground GW detection facility.

2.2 Connection to Geophysics

An underground facility like CEGO can produce important scientific results other than gravity waves. A GW interferometer is essentially a couple of extremely precise and long yardsticks. By simply measuring the relative position of the CEGO test masses to monuments attached to the surrounding rocks it is possible build a formidable strain meter. The operation of this strain meter down to, and well below, the mHz will allow us to study, far from the surface disturbances, the low frequency “hum” of Earth, and all its resonances, with unprecedented precision. The study of these resonances would contribute to give us a view of the internal structure of Earth as well.

At frequencies below that of seismic noise (that is below 0.3 MHz) strainmeters provide an excellent way to measure tectonic strain --- the long-term strain associated with tectonic activity that in turn is associated with the causes of earthquakes. Seismologists are interested in measuring the strain rate over years and in particular in looking for changes. The CEGO cavities could provide an excellent place to install a variety of other geophysical instruments,

1.2 Technical feasibility

In this section, we discuss the technical feasibility of low-frequency gravitational-wave detection. We first discuss techniques that suppress the Newtonian seismic gravity-gradient noise (Newtonian Noise, NN for short), which is a fundamental lower limit for surface-based gravitational-wave detection. We then discuss other interferometer technologies that should be used to take advantage of NN suppression, in particular the suppression of seismic noise, suspension thermal noise and radiation-pressure noise.

2.2.1 Suppression of the Newtonian seismic gravity-gradient noise (Newtonian Noise)

The Newtonian Noise arises the random fluctuations of the Earth’s Newtonian gravitational attraction acting on the test masses (mirrors) due to the ever-present seismic microscopic-motion of the Earth’s crust. According to Hughes and Thorne,[22] the Newtonian Noise, at ground level near the LIGO sites, is $(S_{x\,gg})^{1/2} \sim f^{-4}$ for f>10Hz and $(S_{x\,gg})^{1/2} \sim f^{-2}$ for f<10Hz. This scaling consists of two parts. The Earth’s motion has $(S_{x\,\mathrm{Earth}})^{1/2} \sim f^{-2}$ for f>10Hz and $(S_{x\,\mathrm{Earth}})^{1/2} \sim$ constant for f<10Hz. This motion (of the inhomogeneous Earth crust) generates fluctuation in the Newtonian gravity, which in turn induces test mass motions following Newton’s second law, therefore putting extra factor of f^{-2} into $(S_{x\,gg})^{1/2}$. It is calculated that NN in the LIGO sites can prevent the sensitivity of Advanced LIGO from further improvement below ~20 Hz.[22] In order to have a more specific comparison, we compare with the Standard Quantum Limit for a 1000 kg test mass, which may be the best conceivable sensitivity an interferometer can reach in the next decade: getting the Newtonian Noise below this means that we make it negligible for all purposes. [The concept of the Standard Quantum Limit will be explained in Sec. 2.2.3.] According to Hughes and Thorne, the Newtonian Noise at LIGO sites can cross this criterion anywhere between 20 and 30 Hz, depending on episodes of higher or lower seismic activity.

In calculating the NN noise, it was immediately obvious that locating the detector underground would substantially reduce the NN. It is measured that the seismic noise in the frequency band of interest, is often two orders of magnitude smaller underground, though the detailed frequency spectrum must be measured at each particular site. However, due to the fourth power slope as a function of frequency of the NN perturbations, simply going underground would gain only a factor of ~3 in frequency, bringing the detection limit, down to 8-10 Hz only.
It was only recently realized, and calculated,[66] that the NN can be in large part cancelled by suitably carving a deep underground cave of spherical, or better, elliptical shape, around the interferometer test masses. NN suppressions of several orders of magnitude may be possible, thus making GW detection possible, under Earth's surface, possibly as low as ~1 Hz. Other conceptual advances in suspension thermal noise and radiation pressure noise reduction techniques[26] indicate that we will be able to take advantage of the NN reduction and measure GW, on Earth, in the 1 to 10 Hz frequency range. The preliminary, analytical calculations of the NN cancellations presented in Aspen are carried out in the approximation of infinite, and perfectly uniform rock (no effect included from the surface to air interface up above). Model refinements are necessary to validate the model, introduce realistic seismic activity levels, and better define the useful frequency span of the actual NN cancellation.

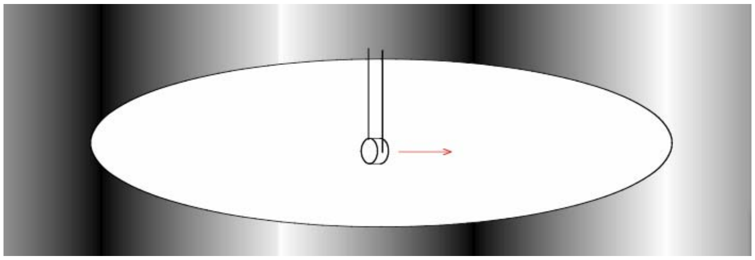

Figure: Scheme of the suspension of a GW detector test mass to minimize the NN.

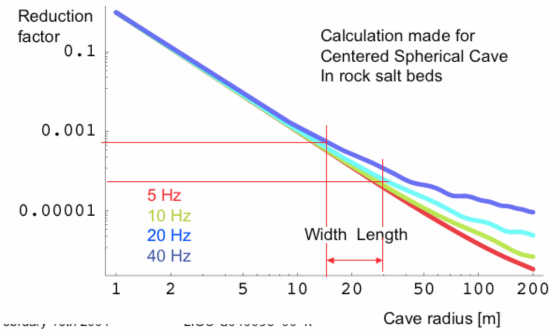

Figure: Calculated reduction factor of NN amplitude as a function of cave size. The initial point normalized to 1 (cave radius 1 m) is expected, for symmetry reasons, to be already substantially better than the case of a surface interferometer (typical height of the beam of 1 to 2 meter above flat ground). This initial calculation is made for a spherical cave, the NN reduction factor for an elliptical cave (aligned with the beam) is expected to be in between that of the attenuation factor for a sphere of diameter equal to the minor and the major ellipse axis. Corrections have to be made because of rock stratification and nonuniformities, and the effects of the surface, a few hundred meters above, have to be taken into account.

Dedicated seismic measurements are being scheduled, at least in one site, to measure the seismic activity as a function of depth and rock stratification and provide suitable data and include these effects in the model.[66] It seems plausible though, that NN can be sufficiently suppressed to allow GW detection at frequencies as low as 1Hz.

2.2.2 Suspension Thermal Noise

The suspension thermal noise can also impose a limit to the sensitivity of a LF interferometer, which is often close to that of the NN. An underground facility allows the use of suspension wires much longer than they can be implemented in a ground-surface facility. Wells are easily core drilled underground. Long mirror suspension systems 50-100 m long, or even more, can hang down wells, instead than from tall towers on the surface. Longer suspensions push the suspension thermal noise to lower frequencies, with a frequency cutoff descending as $1/\sqrt{l}$. [27, 28] It appears feasible to built interferometers sensitive to GW signals down to 6-7 Hz simply using 12-15 m long wires and presently available technologies. It is entirely possible to further lower the suspension thermal noise limit below 6-7 Hz simply using the customary fused silica suspension technology and longer wires. Longer wires would continue to push the STN at lower frequencies. Longer wires would unfortunately also drive the wire's violin modes in the detection band and this problem would have to be dealt with, possibly with active monitoring and damping of the violin resonances.[67] It cannot be excluded also that advancing technologies would, in the future, further reduce the suspension noise without requiring much longer wires.

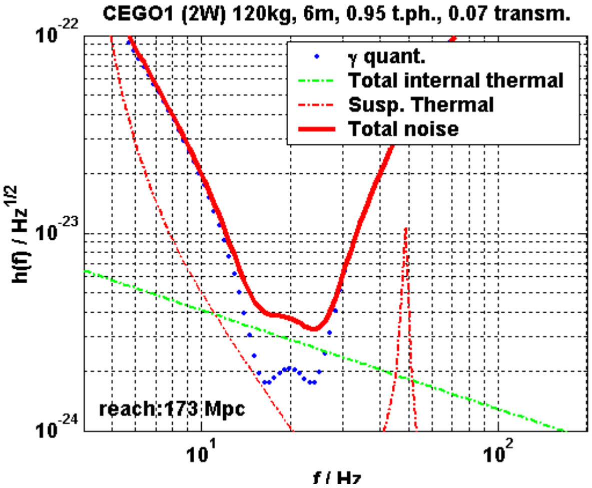

Figure: The thin red line illustrates the limitations introduced by the suspension thermal noise at the left of the sensitivity area, and of the wire's violin modes, peak at the right.

2.2.3 Optical noise: Radiation-Pressure Noise and the Standard Quantum Limit

Radiation-pressure noise in gravitational-wave interferometers arises from the random change of the number of photons stored in the arm cavity beams buffeting the test-mass mirrors, and inducing noisy motion. For a Michelson interferometer with Fabry-Perot cavities in the arms, the noisy radiation-pressure has a white spectrum below the cavity bandwidth. The radiation-pressure noise, once referred to displacement, is $\sim I^{1/2}/(mf)^2$, where m is the mass of the mirror, and I is the power circulating in the arm cavity. On the other hand, the familiar shot noise is $\sim 1/I^{1/2}$. Radiation-pressure noise and shot noise are complementary to each other; in fact, for conventional interferometers (Michelson interferometers with Fabry-Perot cavities in the arms, and no signal recycling[12]) and conventional readout scheme (detecting the phase quadrature of the output light), the total noise can never fall below a so-called Standard Quantum Limit, given by

$$h_{SQL} = \sqrt{\frac{8\hbar}{M\Omega^2 L^2}} = 2 \times 10^{-24} \left(\frac{100\,\mathrm{Hz}}{f}\right) \mathrm{Hz}^{-1/2}$$

The Standard Quantum Limit can also be derived from the quantum theory of measurement,[68] as a result of continuously measuring the displacement of a free mass. The Standard Quantum Limit can be surpassed, using so-called Quantum Non-Demolition (QND) techniques.[69] Designs of QND interferometers have also been proposed over the past several years, which seem plausible for realization around the end of the decade.[70-73] It has also been shown that the quantum noise of the signal-recycling configuration of Advanced LIGO can also beat the Standard Quantum Limit moderately.[74-76] The use of squeezed vacuum can also enhance the sensitivity of QND interferometers.[70, 77, 78]

However, even if QND techniques were not to be used, simply increasing the mass of the mirror can increase the sensitivity by lowering the radiation-pressure noise and, at the same time, the Standard Quantum Limit. The global improvement is proportional to $m^{1/2}$: for signal-recycled Fabry-Perot interferometers with increasing mirror mass m, the optical parameters can be adjusted to give a noise spectrum $[S_h(f)]^{1/2}$ that scales as $m^{-1/2}$ for all frequencies.[76] Alternatively, one can choose to only improve the low-frequency sensitivity, in regions where radiation-pressure noise dominates, which is proportional to $1/m$, by fixing all optical parameters and simply increasing the mass.

It should be noted that, for low-frequency detection, a low laser power is required, and mirrors of somewhat lower transparency can be tolerated. Mirrors of not extreme optical properties (required, instead, in the high beam power of the Advanced LIGO and Virgo interferometers) can be manufactured up to weights of 150 to 200 Kg, which can lower the noise by a factor of ~2 in amplitude globally with respect to the case of Advanced-LIGO mirrors, or can alternatively lower the low-frequency portion of the spectrum (where dominated by radiation-pressure noise) alone by a factor of ~4-5 in amplitude

2.2.4 Choosing the site

Due to Earth's curvature, a surface interferometer cannot be much longer than 4 or 5 Km without having to sink the beams in the ground. In a deep facility straight tunnels of much longer length can be bored, if necessary, with no additional complications. To be reminded that, with all other parameter kept constant, the reach of the interferometer is directly proportional to the arm length, and the covered volume/detection rate is proportional to its cube. Since the tunnel length (and beam pipe) only contributes linearly to a small part of the facility cost, it is quite advantageous to build up the maximum possible arm length.

From the facility potentiality point of view, it should be noted that the cheapest deep tunnel has a cross section of 20 to 35 m^2. The large underground facility tunnels would easily house multiple beam pipes for multiple interferometers. For example, all four interferometers considered in the Aspen presentation (including an Advanced LIGO-like one) can fit in a fraction of the tunnel cross section and therefore maintain the potential to add more pipes if further technical advances allowed the construction of interferometers for detection at even lower frequencies. The choice of the facility site (and rock type) can strongly affect the facility limit performance and the digging costs. Extensive geological studies are needed for a judicious site choice.

It is worth noticing that access, rock extraction facilities, and other infrastructure costs are a quite significant fraction of the facility costs. These infrastructures would remain available in case, at a later time, an additional detector rotated at 45 degrees was desired to cover the orthogonal GW polarization. This second "rotated" facility would incur strongly reduced digging costs.

3. Technical and scientific spin-offs

The measurable effects of GW are extremely small, of the order of 10^{-21}, 10^{-22}, or even smaller for periodic sources. Measuring the effect of an incoming gravitational wave amounts to measuring the coherent vibration of a 40 Kg mirror with an amplitude smaller than one thousandth of the diameter of a proton (10^{-18} to 10^{-19} m over the length of a few kilometers), despite the fact that the atoms at the surface of the same mirror are literally boiling and roiling up and down, pushed by thermal excitation over distances a million times larger (~10^{-12} m) than the signal amplitude. No experiment have ever measured so small effects over so large a background and, until recently, it was believed that GW would ever be hopelessly too small and too difficult to measure. It is only thanks to enormous technical advances in several measurement and manufacturing fields that detecting GW is finally becoming feasible. GW detectors are therefore pushing the technical envelop of the status of the art in many fields.

It is also very expensive to build GW detectors, although their cost pales in comparison with other fields like space exploration and high-energy physics. It is then logical to ask:

- What are the frontier technologies that Chinese scientists will have to master?
- Can they manage to build a GW detection facility that has significant scientific impact?
- Is the present status of the Chinese know-how sufficient?
- How will the Chinese economy profit these advances?

The following is a partial list of the key technologies, followed by some discussion to partially answer the above questions.

3.1 Technologies involved

Laser technology: high power and ultra stable lasers (stabilized to unprecedented levels both in amplitude and in frequency) have to be employed. The highest available power is necessary to reduce the shot noise of the distance measurement. Basically we are measuring distances (10^{-18} m) that are much smaller than the wavelength of a photon (10^{-6} m); this can be done only by averaging over many atoms. In theory the measurement precision can be improved without limits increasing the precision by a factor of two for each factor of four of increased laser power. In practice though, this unlimited precision advancement is limited by the laser frequency and power stabilization. The required stabilization goes way beyond what is available on the market and tight collaboration between the best laser developmental laboratories and the GW observatories is continually ongoing.

Optics: large-size mirror substrates and mirror coating with extremely low thermal noises (mechanical Q factors of $>10^8$ for substrates), extremely low optical losses coatings (light absorption $<10^{-7}$, to compare with the 5-8% of a metal coated mirror), extreme uniformity (optical thickness of the mirrors to be flat to $<10^{-8}$ m), exquisitely good optical profiles (precise to $<10^{-8}$ m), extremely low light scattering fraction (<~ppm) have been developed and are used for the measurement of GW. The mirrors are one of the fundamental limitations to GW detection and still require further advances to improve the future detection sensitivity. Most of the extreme specifications listed above have been developed purely for the GW measurements, which are presently driving the development of this field. The GW detection scientists are continuously scouting for new solutions to push the limit in collaboration with several mirror manufacturers.

The main thrusts of mirror development are on manufacturing mirror substrates of lowest mechanical and optical losses and highest weight, on coating with similarly good properties and of better optical surface finish. The development of Large sapphire mirrors at the Shanghai Institute of Fine Mechanics is an example of this.

Advanced optics concepts 1: Even with the highest power available lasers, there would be not nearly enough laser power available to perform the GW measurement with sufficient precision. Sophisticated optical techniques including implementing Fabry Perot cavities in the main Michelson interferometer arms, power and signal recycling mirrors, and other solutions have been developed and are continuously being perfected in order to bottle up enough light in the interferometer to make the measurement with sufficient precision. No large scale experiment has ever implemented such high level of sophistication.

Advanced optics concepts 2: Optical measurement techniques are also studied in order to mitigate the mirror thermal noise limitations. After choosing the lowest thermal noise mirror materials, the mirror thermal noise can be further reduced by optical means. The reason why one can measure the mirror position to less than one millionth of the random thermal "dancing" distance of the atoms at the mirror's surface is that the laser beam averages over a large number of atoms. There exist three kinds of identified thermal noises, the thermoelastic noise of the material,[31, 32] the substrate thermal noise[30] and the coating thermal noise.[29] All three are depressed by larger beam spots w, although with different scaling laws. Thermoelastic noise is suppressed with the $1/\sqrt{w^3}$, coating thermal noise decreases with 1/w, while the intrinsic thermal noise of the substrate is suppresses with a slower $1/\sqrt{w}$ law. It is therefore important to use large cross section laser beams to measure the position of the mirrors and average on more atoms. The most commonly used beam profile is the Gaussian beam, the beam that naturally fills optical cavities made with flat and spherical mirrors. Unfortunately, a Gaussian beam profile, with the tight diffraction constraints of a GW detection interferometer, is limited to a beam width of about one sixth of the mirror diameter, thus limiting the surface averaging process to <~2.8% of the mirror's surface. The rest of the mirror's surface is "wasted" for thermal noise reduction. Flat top, non-Gaussian beams, filling optical cavities made with non-spherical mirrors, are presently been developed to sample over a larger fraction of the mirror surface.[79] These beams would be first time tested in China, in a relevant size interferometer, if the Beijing developmental 200 m interferometer was built timely.

Advanced optics concepts 3: As discussed in the preceding chapter, even disposing of unlimited laser power, and after solving one way or another the thermal noise limitations, the measurement precision is still limited by the Standard Quantum Limit. The SQL can be depressed by simply using heavier mirrors, and this is an active development thrust; but there is a limit on how heavy a mirror of sufficiently good optical and mechanical characteristics can be manufactured. Sophisticated optical techniques that circumvent the SQL (Quantum Non-Demolition techniques for example), are being studied and developed for future advanced measurements and/or to widen the interferometer sensitivity frequency band. These include modifying the prevalent Michelson topology into a Sagnac one.

Control technology: The price to pay in using interferometric techniques is that interferometers have to be kept in lock in order to operate properly and to perform the measurement to the desired precision. Keeping these interferometers in lock is increasingly difficult as more and more nested interferometers are implemented to push the performance. The suspended mirrors have to be positioned and kept at the interferometer lock distance with precisions in excess of 10^{-12} m, of course without introducing control noise on the mirror position in excess of the $10^{-18} – 10^{-19}$ m level expected from the GW signal in the frequency band of sensitivity. This control performance can be achieved only through hierarchical mirror control techniques, first introduced by Virgo, now being implemented in TAMA, and, in future, in Adv-LIGO.

Digital control techniques: The hierarchical controls, and many other instances in the interferometer requiring multiple interlocking nested control loops, require the use of real time digital data processing. Specialized, extreme characteristics, fast DSP, fast and high resolution ADC and DAC have been developed and built to satisfy these requirements, and are still being improved to meet the growing requirement difficulties. These are cutting edge electronics, with continuous interaction with advanced computing, analog sensing, telecommunication, High Fidelity acoustics, and other consumer and strategic electronics fields.

Seismic attenuation: Earth's crust is subject to continuous, random, seismic motion, with amplitude many orders of magnitude larger than the GW signal. It is necessary to suspend the interferometer mirrors by means of seismic attenuation chains. These are chains of pendula for horizontal attenuation alternating with vertical attenuation filters. These filters for higher frequency interferometers like Adv-LIGO can be manufactured with simple cantilever blade springs. Lower vertical resonant frequency springs, provided with various techniques of "anti-springs" to lower their resonant frequency and extend their seismic attenuation frequency band, have been designed and implemented for Virgo and are required in GW interferometers sensitive to lower frequency. Various "anti-spring" techniques have been developed ranging from magnetic AS, geometric AS and Euler springs.

To be noted that as one progresses along a seismic attenuation chain, and the residual disturbance decreases, one has to increasingly worry about internal noise generation, like creep, creak, and up conversion of relatively large excursion and lower frequency movements. This increasing sensitivity to internal mechanical noise sources continues all the way to the level of the suspension mechanical thermal noise. Building a Seismic attenuation and mirror suspension chain requires mastering a set of increasing sophisticated material technologies that includes high level metallurgy and high performance materials (for example maraging steel for the springs and the wires), possibly glassy metals for the lowest levels springs in the attenuation chains, all the way down to fused silica or monocristalline suspension fibers and flex joints at the mirror level.

Seismic sensing: Advanced and low cost accelerometers for Newtonian Noise subtraction (for either underground facility use or for subtracting NN in existing surface facilities to improve their low frequency range) have to be developed.

Advanced (highly directional, high sensitivity and UHV compatible) accelerometers have also been developed for feed back in active damping of the resonant modes of passive attenuation structures or active seismic attenuation systems.

Active attenuation techniques have been developed for the initial stages of a seismic attenuation chain for Adv-LIGO. These extremely sophisticated and complex techniques are limited by the mechanical sensor sensitivity, they are not strictly necessary, as shown by the Virgo super attenuators, and they would probably not be useful in an underground facility where the natural seismic motion amplitude is not much larger than the available instrumental sensitivity. They may be useful, though, in limited applications like test facilities.

Vacuum technology: the measurement of GW requires large diameter pipes housing the laser beams into Ultra High Vacuum. Even minute traces of gas, excited by the thermal and mechanical stresses along the tubes, would generate disturbances much larger that the GW signal. The 22 Km of 1.2 m diameter UHV pipes implemented in the three observatories at LIGO and Virgo enclose some of the largest and highest vacuum volumes on Earth.

To achieve these HV performances both Virgo and LIGO had to utilize very low emissivity materials (specially steels) and develop special processing techniques.
Vacuum techniques like quiet pumping techniques (sublimation pumps) have been also pushed and perfectioned. It is worth noting that Chinese scientists have been at the forefront of these developments at Virgo.

General engineering: the construction of a GW interferometer entails the construction of large structures and, for underground facilities, large excavations. The construction of a GW detection facility will require the use of modern engineering and project management, perhaps following the models of the LIGO and Virgo realizations.

Search for GW signal is forcing advances in several data handling, data processing and data analysis techniques like:

- Noise treatment techniques
- Extraction of weak signal from large noise background
- Mathematical filtering methods
- High speed computing
- Large database and large complexity algorithms
- High-speed computers

Most of these techniques have direct applications for commercial, scientific, or military use.

3.2 Know-how requirements and training

In order to build a GW detector, Chinese scientists do not need to master all of these technologies to the point of in house producing all components. In most cases it will be sufficient to master these technologies to the point of correctly implementing and operating them. Given the scientific necessity of new GW detection facilities, foreign scientists have all the interest to tutor Chinese scientist to a level sufficient to guarantee the success of the endeavor. For this reasons the GW community will gladly host and train Chinese scientists in implementing, operating, and maintaining the existing facilities for a period of few years.

In the course of these activities, the Chinese scientists will become proficient in these key technologies and train younger graduate students and postdoc. These trained new scientists will be precious in a rapidly growing country.

The process of conceiving, designing and building the present GW detectors took decades. All design and technologies developed specifically for GW are already public or will be made available for the effort to build a Chinese observatory. Collaboration with the international GW community will help China to speed up the process to less than a decade.

International enterprises of great scientific importance always attract the best scientists from everywhere. Let's take the example of CERN. Not only CERN retains a large number of European scientists, but scientists from every nation travel to Geneva to work at CERN. This can be said of any scientific enterprise of truly general importance. A prestigious scientific enterprise like CEGO not only will attract and train a new generation of Chinese scientists, but it will also attract many foreign scientists, including some Chinese scientists now active elsewhere.

4. Starting the China, Einstein, Gravity wave Observatory (CEGO)

4.1 Past preparatory work

Following all of this renewed and expanded interest, a group of Chinese and US scientists has organized a very successful first workshop with the specific aim to propose a Chinese GW detection project. This workshop, held in Beijing from the 2nd and the 4th of March, has immediately attracted 70 scientists [appendix list of participants and institutions] of 20 separate institutions [appendix separate list of institutions] and received letters of support from GWIC (Gravitational Wave International Committee [appendix, letter of Cerdonio] and of the main existing GW observatories [appendix, letters from LIGO, Virgo, EGO].

This first workshop was mostly attended by Chinese scientists, with the participation of a small number of external scientists. It verified the very keen interest of Chinese scientists in this new and exciting field. The workshop participants pledged to work towards the development of a GW detection observatory in China. It was decided that a formal proposal for a Chinese GW observatory should be put forward and proposed to the Chinese scientific community, its government and the world scientific community at large. This proposal is the first step in that direction.

It was decided that the proposed observatory, named CEGO (China Einstein Gravitational wave Observatory) would be completely open to the international community and seek its support.

It was also decided to organize as soon as possible a larger, international, workshop to be held, also in Beijing, taking advantage of the pledged support of GWIC and of the other existing GW Observatories with the aim to attract the largest number of new contributors and start organizing the effort towards the new GW Observatory in China.

Keyun Tang will accept the GWIC invitation to present this initiative to the next GWIC meeting in July 2004.

Tang Keyun, Zhu Ren-yuan, Riccardo DeSalvo, Wang Yunyong, Zhu Zhang, Zhu Zhong-hong, Coleman Miller, Bao Pan Hui, [three or four more names] formed a temporary steering committee to take charge to organize this new workshop and initiate the process leading to the Observatory proposal.

Before and during the forthcoming workshop a number of well-known scientists will be contacted and invited to form an international scientific board in support of this initiative.

4.2 Roadmap towards an Underground Low Frequency Gravitational Wave Interferometric Detector Facility

Here is a list of general steps toward the CEGO interferometer:

1. Get seed people trained in existing GW interferometric detectors and build up a home staff at the hosting institution.
2. Design and then build a local test interferometer in Beijing to train people on building instruments on their own, to get proficient in all key technologies, and to test new technologies.
3. Study the practical extent of NN, STN, and RPN suppression techniques.
4. Study the different geological options and digging techniques and identify a suitable facility site.
5. Design an optimized facility in view of a sequence of increasing Low Frequency performance interferometers.
6. Design a first interferometer, based on existing technology, but aiming at the lowest achievable sensitivity range with small and reasonable extrapolations of existing techniques.
7. Start digging the tunnels and building the facility.
8. Build the designed interferometer(s).
9. Install the interferometer(s) in the facility.
10. Based on the results and achievements of the first interferometer(s), design successive generations of additional, or replacement, detectors pushing the frequency and/or the sensitivity limit as low as possible until reaching the limit of the facility.

Points 1 to 6 should be performed within a 3 to 4 year period to prepare a detailed proposal in view of a final approval. Points 6 to 10 should follow up, within another 3 to 5 year period, after final approval is secured.

1) Get seed people trained in existing GW interferometric detectors.

Trainee should be sent to learn seismic attenuation, controls, control electronics, advanced laser and laser beam technologies, large Ultra High Vacuum technologies, etc.

LIGO, Virgo/EGO and TAMA have already expressed their availability to host Chinese physicists and train them in the trade. This would take place either at the Observatories themselves or at the home R&D laboratories. About 12 to 18 scientists should be involved in this program.

Obviously a substantial home team will be necessary to support the project in all its aspects.

2) Build test interferometer(s) to train personnel on building and running large advanced instruments

The test interferometer should incorporate all the relevant techniques, seismic attenuation, controls, control electronics, advanced laser and laser beam technologies, large Ultra High Vacuum, to verify the preparation level of the trained personnel, in preparation of the installation of the large interferometer on the observatory site.

The test interferometer should also incorporate at least some element of novelty. It is suggested to build a ~200 m interferometer with two parallel Fabry Perot cavities. The experiment is close to be one of the simplest possible configurations and still require implementation of all the basic techniques necessary to run a full-scale interferometer. This interferometer would initially be instrumented with spherical mirrors and support Gaussian beams. The mirrors would be suspended with TAMA-like suspensions and hierarchical controls. The twin beam configuration would allow laser stabilization for frequency noise suppression. After debugging the two cavities with Gaussian beams, the test interferometer would be converted into a flat top beam profile interferometer to test the lower thermal noise performance of these beams in a fully suspended, relevant scale interferometer. This novel measurement has not yet been performed and would have its own scientific importance. The flat top technology, if successful, may well be implemented in all old and new interferometers to suppress their thermal noise and extend their sensitivity and reach. Of course this is simply an initial, but concrete suggestion, the real test interferometer should be designed and built only after sufficient scientific debate and evaluation of different options,

3) Study the practical extent of NN, STN, and RPN suppression techniques.

Although using, or moderately pushing, the available technologies allows the construction of GW detection interferometers sensitive at substantially lower frequencies, extensive R&D is necessary to mature these technologies and prepare them for actual implementation in a large-scale instrument.

A partial list of these advanced R&D items to be covered include:

- Larger mass mirrors for RPN reduction
- Longer and higher quality factor suspensions for STN suppression
- Newtonian Noise reduction strategies
- Lower frequency seismic attenuation techniques
- Improved hierarchical controls
- Environmental measurement and controls

The first three items are the most relevant for LF, underground, operation. The in depth study of these and other items is necessary to allow a meaningful design of a real full scale interferometer. Some of these technologies can be obtained at low effort from, or in collaboration with, existing R&D labs. Gathering sufficient know how on other items will require the organization of dedicated task forces with adequate resources.

4) Study the different geological options and digging techniques and identify a suitable site for the real CEGO facility and design the facility accordingly.

A dedicated team of geologists, geophysicists and mining engineers should join the existing efforts to gather the necessary general information and start immediately to scout the Chinese country side for the possible site.

5) Design an optimized facility in view of a sequence of increasing Low Frequency performance interferometers

The CEGO mission is to detect GW in Lower Frequency ranges than existing detectors. This could be done by means of a properly shaped underground facility to depress NN. Ellipsoidal shaped caves around the test mass have been calculated to strongly depress NN. As discussed in chapter 2 the analytical model, based on the assumption of an infinite and perfectly uniform rock background, needs to be replaced by a numerical model including realistic rock stratification, real seismic activity, the effects of Earth's surface up above, etc. The numerical model will allow us to make the technical and scientific design tradeoffs for the interferometer and to make the best choice of facility location for the task as well as of the best cave shape and sizes. This study will require the knowledge of the level of seismic noise versus depth, the effects of rock stratification and rock modifications in a number of selected candidate sites and other site dependent variables. For this it will be useful to join existing data collection efforts (the expected Realmonte mine measurements) and to extend these measurements to a few Chinese locations.

6) Design a first interferometer, based on existing technology, but aiming at the lowest achievable sensitivity range with small and reasonable extrapolations of existing techniques.

It is premature to attempt a design of a full interferometer beyond what was already done to generate the four sensitivity curves of figure 2. The design of the actual CEGO intereferometers will be done at the convenient time, based on the existing and rapidly growing experience from other GW interferometers and of the studies of a specialized group in the next 2 or 3 years.

4.3 Staged approach at the CEGO facility

One should first realize that we cannot cover the entire frequency range with a single interferometer. The implementation of interferometers in CEGO will need to go by steps, starting from an easier interferometer sensitive to a frequency range just below, or even partially overlapping, the existing, surface, interferometers and follow up with interferometers sensitive to increasingly lower frequency. The final lower frequency limit of an underground facility is not known yet, it depends on several parameters still unknown and from future advances in mirror suspension and other advanced techniques. Building a sequence of interferometer generations will gradually take full advantage of an underground facility over the arc of several years. Of course such an underground facility needs to be pre-designed for the upgrades to more and more advanced interferometers.

It is also premature to worry about data analysis for now. The international community, working on existing interferometer data, will advance the data analysis know-how without a specific additional effort. While it would not be advisable to spend too much effort, at this stage, in data analysis, it would still be wise to encourage a group of Chinese scientists to join the analysis of the data of other interferometers.
In the short term, the CEGO development home team will need a sizeable computer facility to support the simulation and design effort, to run the test interferometer, and an archive for document storage and easy access modeled to the DCC in LIGO.

4.4 Tentative design of the Beijing test prototype

The following is simply an initial, tentative design. Parameters, like for example the 200 m length, are soft parameters, chosen to be significant for testing at least a new feature (the flat beam profile configuration to reduce thermal noise with room temperature mirrors), but have not been fixed yet. Also the proposed interferometer, like the LIGO 40 meters, contains most of the elements of complexity in a complete interferometer, but, at least initially, it is not necessary to implement all of these elements. The task would be too complex for a freshly trained team of scientists. It is of interest though to consider all of these options from the beginning, to prepare sufficient space in the facilities for all the options that will be desired. The following design has to be taken as purely indicative.

4.4.1. Interferometer Configuration

The final interferometer configuration is a Detuned Resonant Sideband Extraction (DRSE) illuminated by a laser beam coming from a Pre-Stabilized Laser (PSL) and detected with homodyne detection method (HD). An Input Mode Cleaner (IMC) and an Output Mode Cleaner (OMC) have been foreseen, as shown in Fig. 1.

The DRSE consists of two Fabry-Perot (FP) arm cavities, a Beam Splitter (BS), a Power Recycling Mirror (PRM), and a Signal Extraction Mirror (SEM). The FP arm cavity consisting of an Input Test Mass (ITM) and an End Test Mass (ETM) is employed to enhance the carrier power inside the cavity. The gravitational wave signal is produced as a sideband of the carrier. The PRM is used to further increase the carrier power for better shot noise.[11] The SEM is used to extract the gravitational wave signal from the arm cavities and prevent it from being averaged out in the arm cavities.[80] It also detunes the center frequency of the response function of the interferometer. The IMC, a ring cavity, cleans the mode of the incident laser beam, thus reduces geometrical fluctuations of the laser beam. It is also used to pre- stabilize the frequency of the light. The OMC, a small monolithic ring cavity, cleans the mode of the output beam, thus removes undesirable DC power for better shot noise.

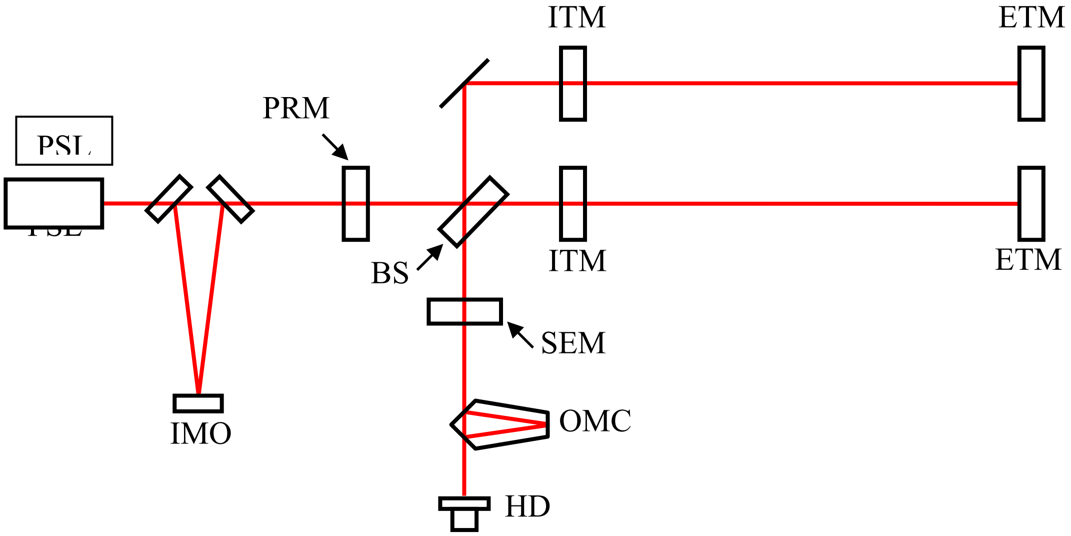

Fig. 1. Detuned Resonant Sideband Extraction with an Input Mode Cleaner and an Output Mode Cleaner.

The important specifications of the interferometer configuration are determined by the target sensitivity of the interferometer as well as some practical constraints. They are summarized in Table 1.

Table 1. Important specifications of the interferometer configuration.

Laser	Power	10 W
IMC	Length	10 m
	Finesse	1,000
Arm Cavities	Length	200 m
	Finesse	2,000
Recycling/Extraction	Power Recycling Gain	10
	Signal Bandwidth Gain	10
	Detuned Frequency	2 kHz
OMC	Length	10 cm
	Finesse	1,000
ITM, ETM	Mass	30 kg

The quantum noise obtained with this interferometer is shown in Fig. 2. Here the quantum noise means shot noise at higher frequencies, radiation pressure noise at lower frequencies, and sum of the two at intermediate frequencies, where the total noise could beat the standard quantum limit due to the correlation of the two kinds of noise.[74] This sensitivity should be sufficient to study the thermal noise characteristics, and improvement with flat top beam, on small (10 cm diameter) mirrors.

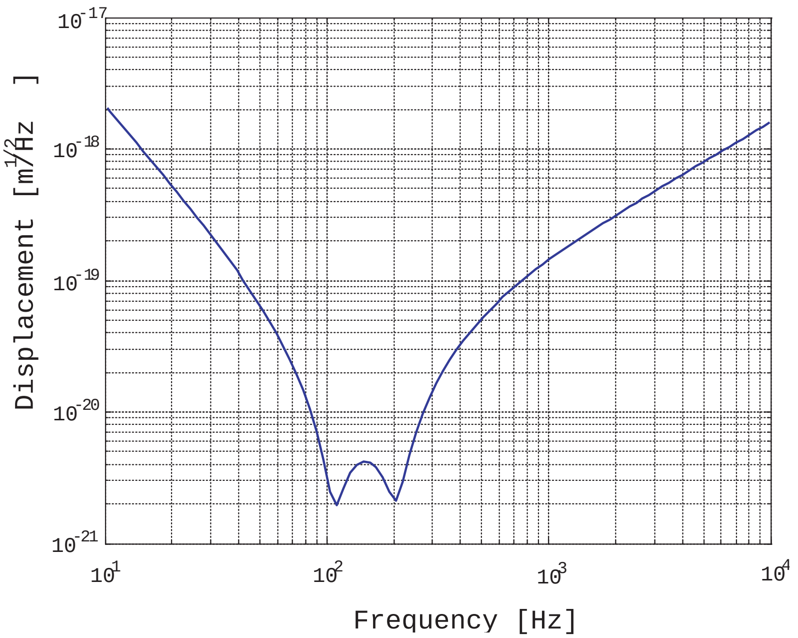

Fig. 2 Quantum noise of the detuned RSE.

4.4.2. Step-by-step Installation

The interferometer will be installed step by step as shown in Fig. 3.

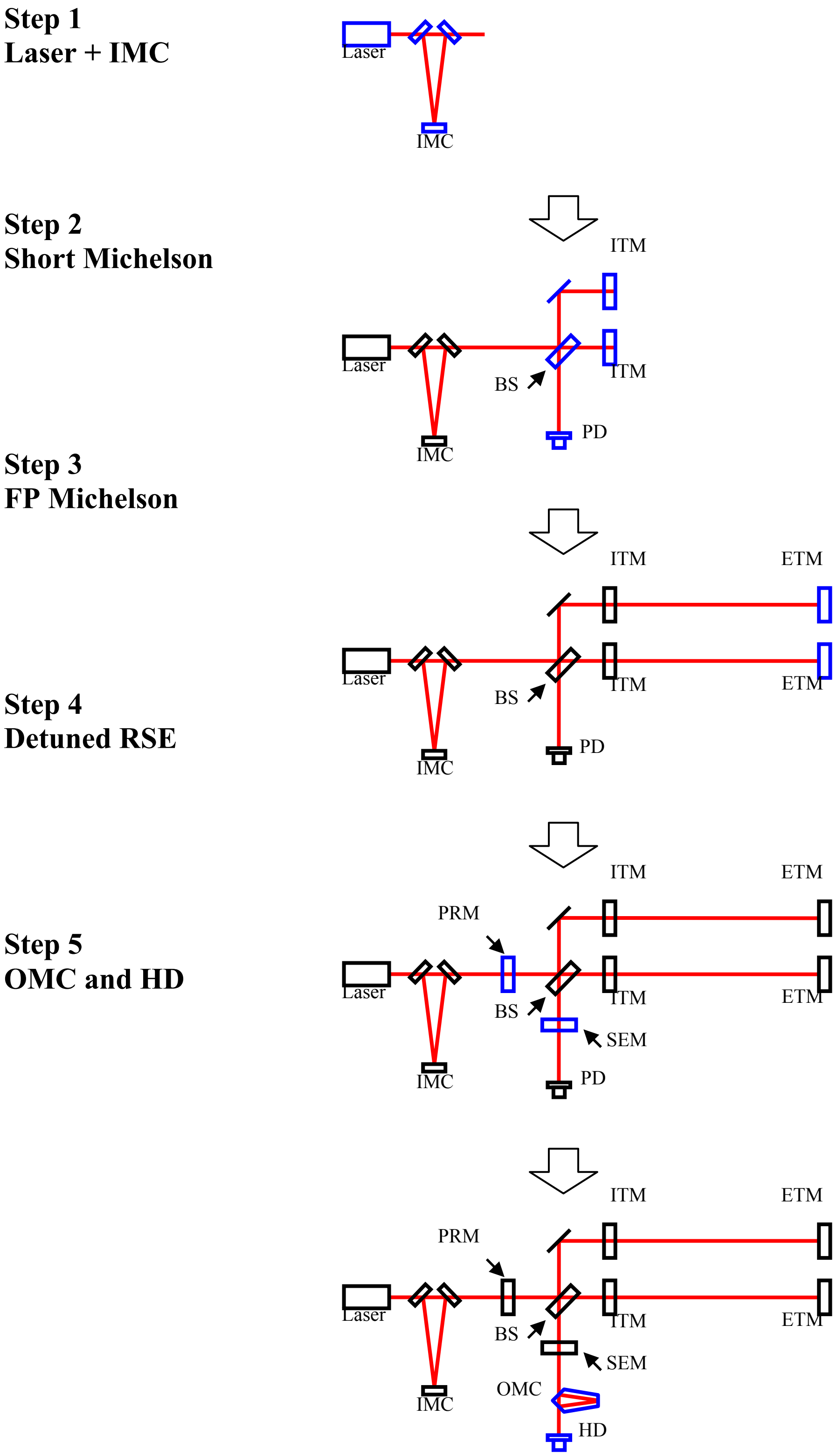

Fig. 3. Step-by-step installation.

4.4.3. Signal Extraction

In order to extract the length control signals for all the degrees of freedom, two phase modulations and double demodulation system will be used. The two sidebands should be resonant in the combined cavity consisting of the power recycling cavity (PRC) and signal extraction cavity (SEC). One pair of the sidebands should be unbalanced to ensure non-zero signal extraction. This can be automatically realized by the detuning features of the interferometer. Moreover, two sidebands should behave differently in the cavity to ensure an independent signal extraction. This can be realized by choosing the frequencies of the two modulations and the length of the PRC and SEC appropriately. Figure 4 demonstrates the example of the two phase modulations and the transmission curves of the PRC and SEC.

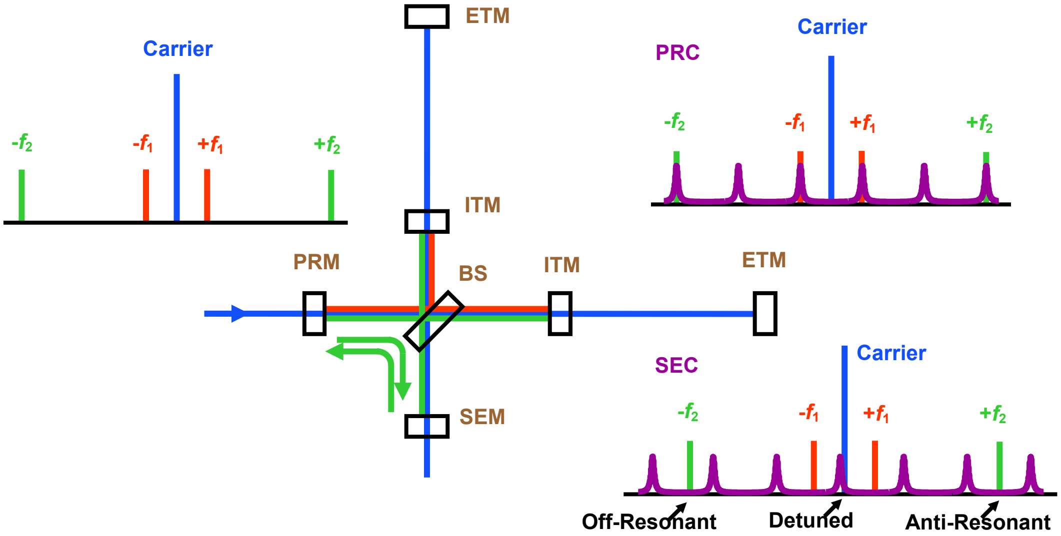

Fig. 4. Two phase modulations used for signal extraction.

4.4.4. Homodyne Detection

In order to avoid the coupling of the non-stationary quantum noise to the interferometer the homodyne detection method should be used to obtain the differential arm length signal which would contain gravitational wave signals.

4.4.5. Flat beam design characteristics

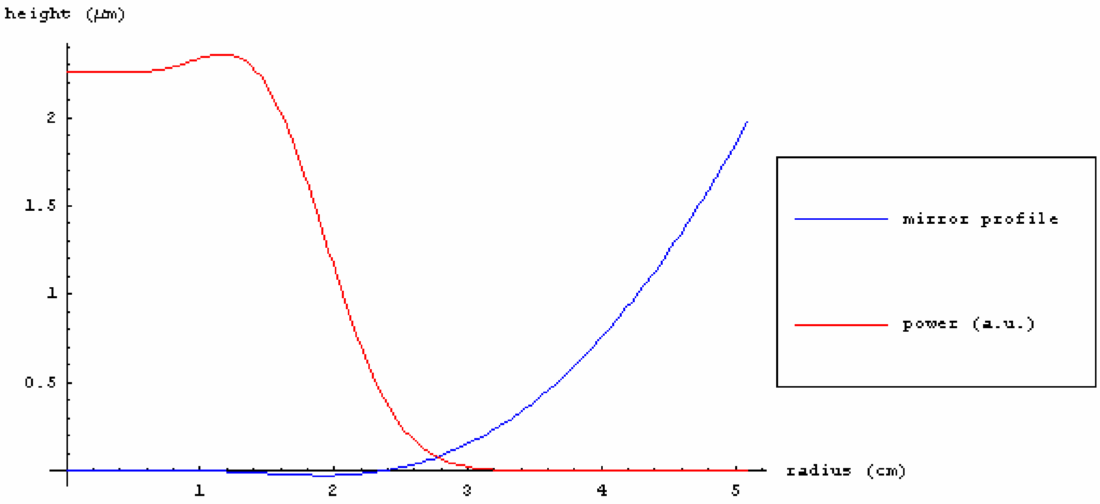

Figure 5. Fabry Perot non-spherical mirror profile and profile of the flat top beam supported in a 200 m long cavity.

Mirrors of 95 mm diameter, supporting 40-45 mm diameter flat top beams have been calculated for a 200 meter long cavity. The mirror outer diameter is fixed by the accepted level of diffraction losses. As a comparison, a Gaussian beam in an equivalent spherical mirror Fabry Perot configuration and with the same diffraction constraints would be 15 mm wide.

4.4.6. Vacuum, seismic attenuation, suspension and mechanics

In order to reduce the design effort and costs of the Beijing prototype, the Seismic Attenuation and Suspension (SAS) system would be directly derived from the new TAMA SAS system which is presently being built and will soon be installed in the next TAMA upgrade. The properties of this SAS system are reported in Akiteru Takamori doctoral thesis[81] and references therein. An example of this SAS system for the proposed twin parallel beam configuration is shown in figure 5. This twin beam SAS would be used for the main FP mirrors and for the BS-folding mirror pair. Single beam SAS, more similar to the TAMA ones, would be used for the other mirrors, while SAS optical benches similar to the ones developed for the Universities of Napoli and Firenze would be used for the input and output mode cleaners.

The SAS was designed to allow quiet TAMA operation in the noisy metropolitan Tokyo environment. It is expected that the proposed configuration, including an additional attenuation stage for added safety, would be sufficient to operate the Beijing test interferometer even in very noisy conditions.

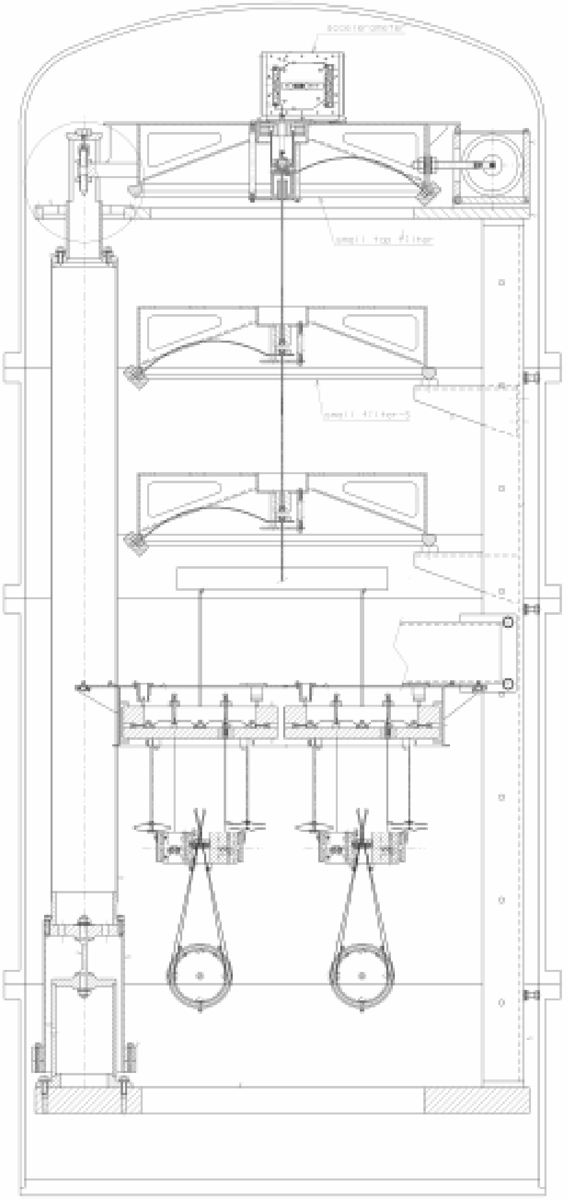

Figure 5: Schematic design of a dual beam SAS system.

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